Use of Solvents in Green Chemistry

Solvent

- A liquid or gas that dissolves a solid, liquid, or gaseous solute, resulting in a solution

- Usually have a low boiling point and evaporate easily or can be removed by distillation, leaving the dissolved substance behind.
- Usually present in the greater amount
- Used to extract soluble compounds from a mixture, the most common example is the brewing of coffee or tea with hot water.

- Common uses for organic solvents are in
  - dry cleaning (e.g. tetrachloroethylene)
  - paint thinners (e.g. toluene, turpentine)
  - nail polish removers and glue solvents (acetone, methyl acetate, ethyl acetate)
  - in spot removers (e.g. hexane, petrol ether)
  - detergents (citrus terpenes)
  - perfumes (ethanol),

- Organic solvents have played a key role in the development of many useful products. They are used in the following areas:
  - Produce pharmaceuticals of the required quantity.
  - In aerosol applications
  - Extraction, recrystallization and the dissolution of solids for ease of handling.
  - Homogenization of a reactant mixture
  - Speeding up reactions through improved mixing

- All of them will be lost to the atmosphere whereas for industrial applications, ‘end-of-pipe’ solutions can be installed to recover much of the solvent for reuse or safe disposal.

- Many of the applications discussed above use volatile organic compounds (VOCs) as solvents because of their ease of removal or evaporation.

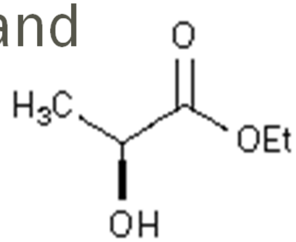
- Adverse health effects originated from the presence of VOCs in the environment include:
  - Conjunctival irritation
  - Nose and throat discomfort
  - Headache
  - Allergic skin reaction
  - Dyspnea
  - Declines in serum cholinesterase levels
  - Nausea
  - Fatigue
  - Dizziness

What are Green Solvents?

- Environmentally friendly solvents or biosolvents, which are derived from the processing of natural feedstocks such as agricultural crops.

- Montreal Protocol identified the need to re-evaluate chemical processes with regard to their use of volatile organic compounds of VOCs and the impact theses VOCs has on the environment.

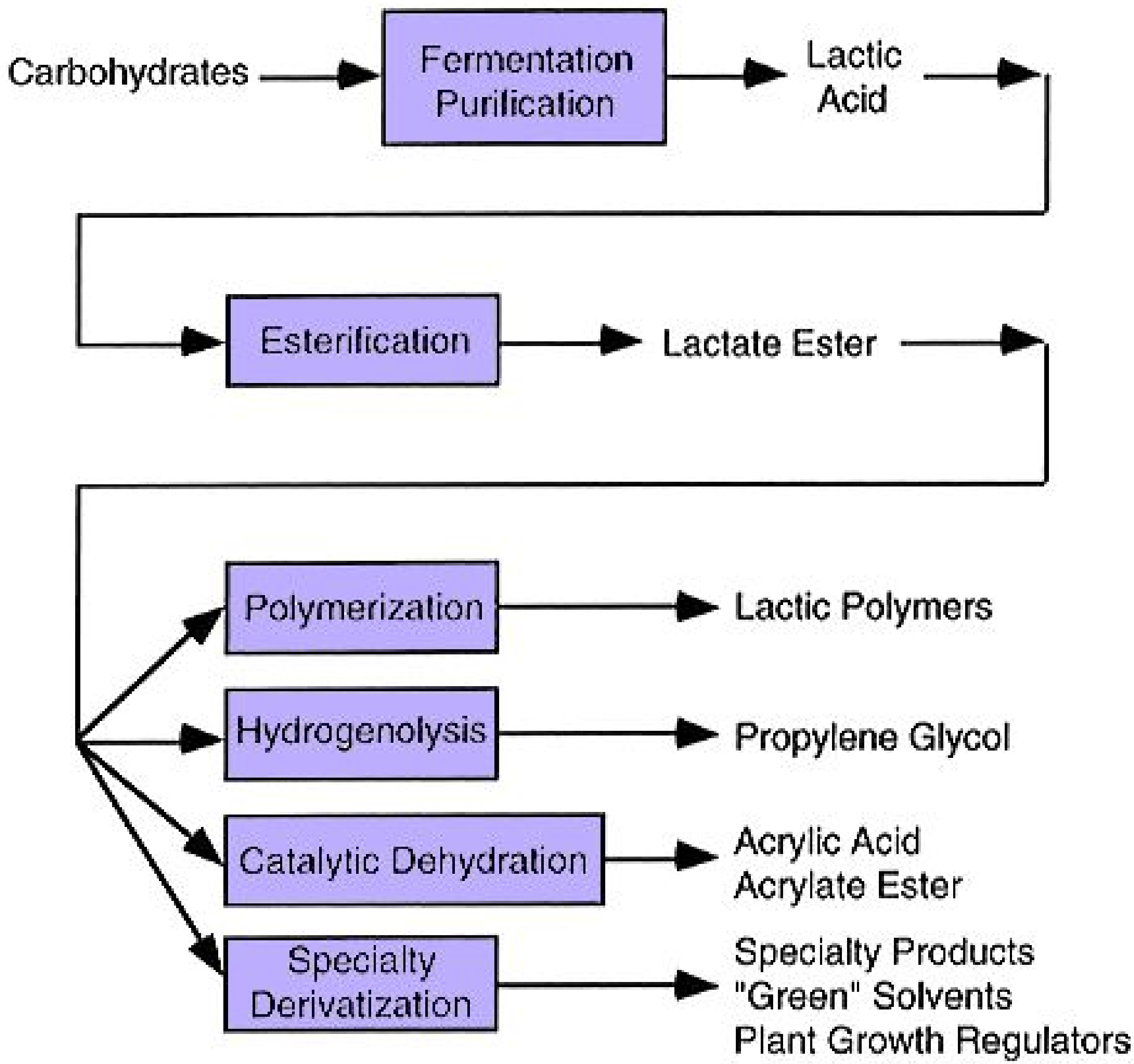
- Ethyl lactate, for example whose structure is shown below, is a green solvent derived from processing corn.
- Ethyl lactate is the ester of lactic acid. Lactate esters solvents are commonly used solvents in the paints and coatings industry



- Numerous attractive advantages including being 100% biodegradable, easy to recycle, non-corrosive, non-carcinogenic and non-ozone depleting.
- high solvency power, high boiling point, low vapour pressure and low surface tension.

- ethyl lactate is an excellent cleaner for the polyurethane industry.

- a high solvency power which means it has the ability to dissolve a wide range of polyurethane resins.


Carbohydrates
Fermentation Purification
Lactic Acid
Esterification
Lactate Ester
Polymerization
Lactic Polymers
Hydrogenolysis
Propylene Glycol
Catalytic Dehydration
Acrylic Acid
Acrylate Ester
Specialty Derivatization
Specialty Products
"Green" Solvents
Plant Growth Regulators

Type of alternatives to using VOCs

- Solvent-free processes
- Supercritical fluids
- Water-based processes
- Ionic liquids
- Fluorous biphase solvents

Solvent-free processes

- There are reactions involving miscible or partially miscible reagents can proceed under solvent-free, mild conditions.

- Solvents are sometimes used unnecessarily because of the process being directly scaled up from laboratory studies with inadequate process development

Raston's synthesis of complex pyridines

- A chemical compound with the formula C_5H_5N.
- The pyridine ring occurs in many important compounds, including the nicotinamides.
- Pyridine is sometimes used as a ligand in coordination chemistry.
- a starting material in the synthesis of compounds used as an intermediate in making insecticides, herbicides, pharmaceuticals, food flavorings....

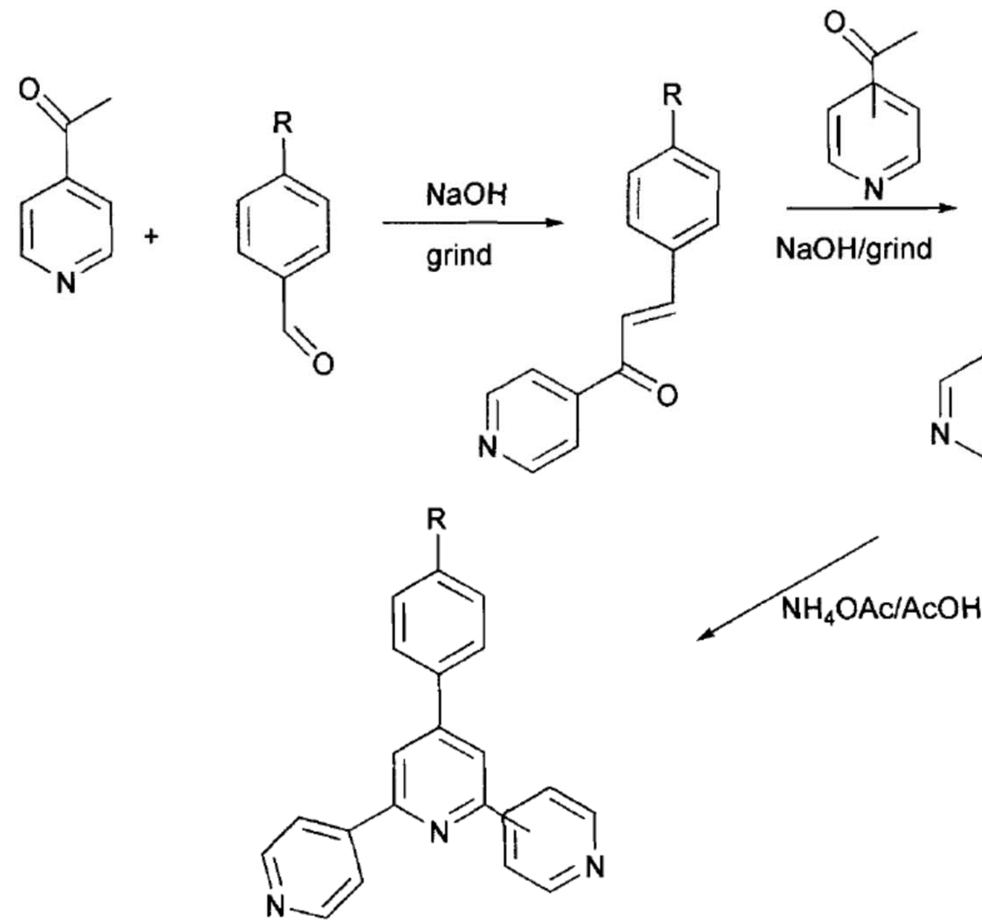
Steps

- Aldol reaction is carried out by grinding together solid sodium hydroxide with benzaldehyde and acetyl pyridine (both are liquids at room temperature) The product is solid which forms after a few minutes.

- On further grinding of the product with the existing or another pyridine, a Michael reaction (nucleophilic addition of a carbanion to an alpha, beta unsaturated carbonyl compound) takes place.

- Both reactions proceed quantitatively, compared to the less than 50% yields normally achieved in solvent-based (ethanol) synthesis. Also, purification by recrystallization in organic solvents is not required.

- Treatment with ammonium acetate and acetic acid



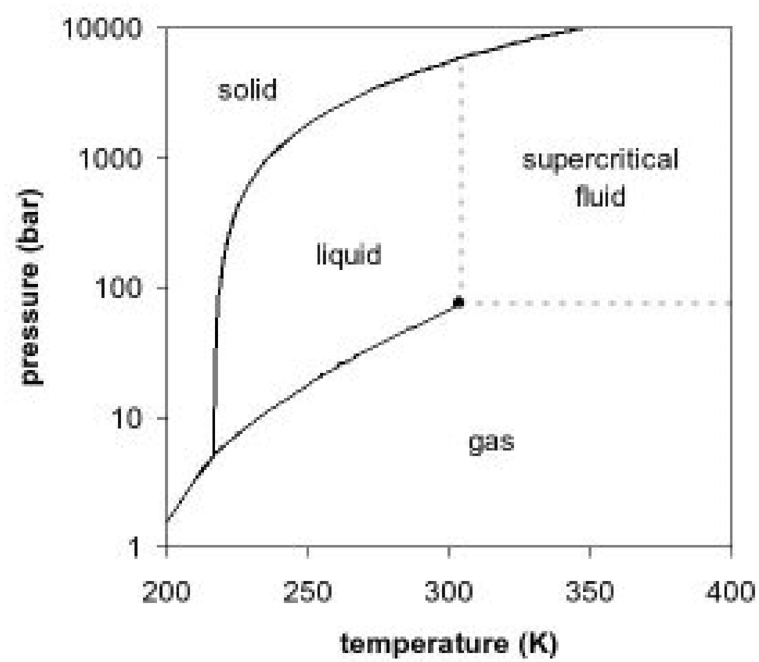
NaOH
grind
NaOH/grind
$NH_4OAc/AcOH$


http://nonnaluna.wordpress.com

Supercritical Fluids

- Defined as a compound which is above its critical pressure and above its critical temperature.
- The material is in a single condensed state with properties between those of a gas and a liquid.
- As the temperature rises it becomes less dense, and when the pressure increase it becomes more dense.
- The fluids have densities nearer to liquids and viscosities similar to gases, leading to high diffusion rates.

- The properties can be adjusted by altering the temperature and pressure, as long as they remain above their critical points.
- By increasing the pressure at the critical temperature, solids can be formed.



- High temperature and pressure free radical polymerization of ethane, to produce low-density polyethene (LDPE) – (Plastic bags, various containers, dispensing bottles, wash bottles)

- The Haber process for ammonia manufacture, which operates above the critical point of ammonia.

Advantages of carrying out a process under supercritical conditions:

- *Improved heat and mass transfer due to high diffusion rates and low viscosities.*

- *The possibility of fine-tuning solvent properties by varying temperature and pressure*

- *A potentially large operating window in supercritical region*
- *Easy solvent removal and recycle*.

Supercritical Carbon Dioxide ($scCO_2$)

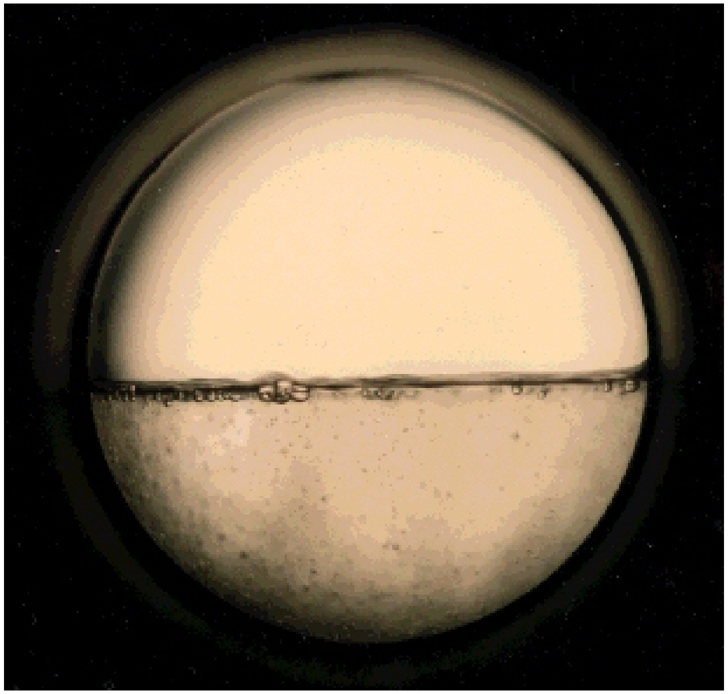
- Separation processes involving distillation are amongst the most energy-intensive processes operated by chemical industry.

- If the separation can be carried out by extraction into a solvent that does not need to be removed by distillation, means there is a potential for saving energy.

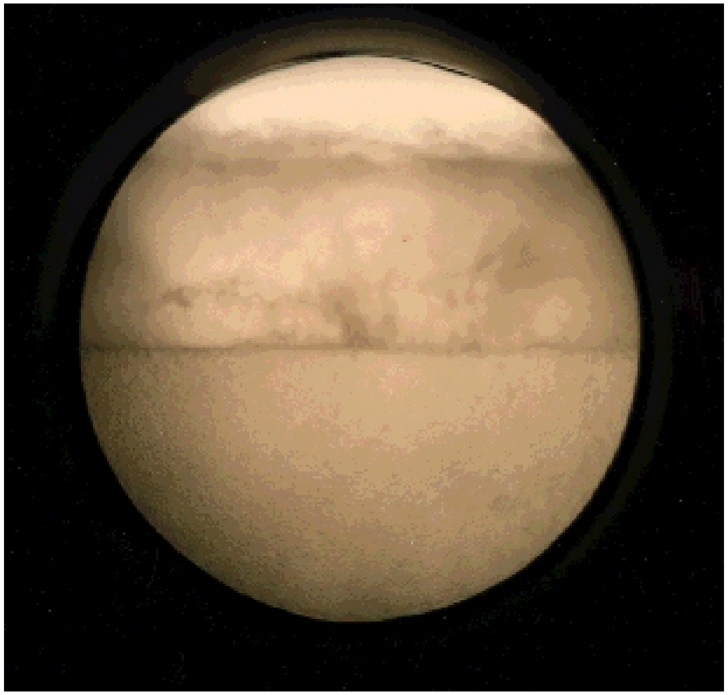
Advantages	Disadvantages
Non-toxic	Rel. high pressure setting
Easily removed	Setting can be expensive
Potentially recyclable	Reactive with strong nucleophiles
Non-flammable	Possible heat transfer problems
High gas solubility	
Weak salvation	
High diffusion rate	
Ease of control	
Good mass transfer	
Readily available	

The making of Supercritical CO_2

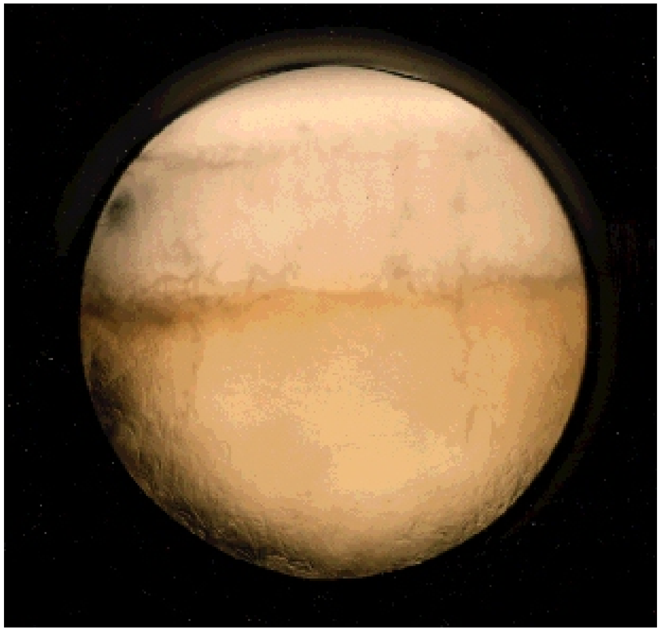
- The separate phases of carbon dioxide. The meniscus is easily observed



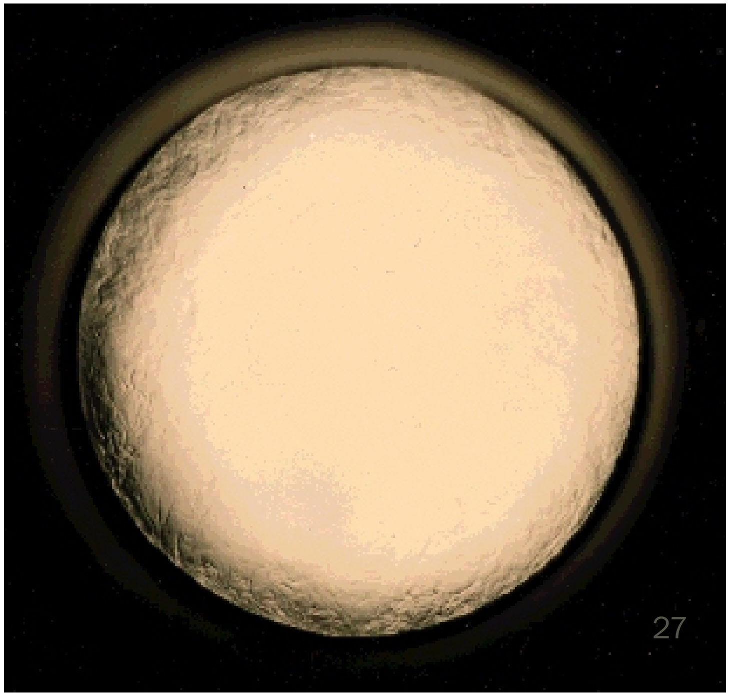
- With an increase in temperature the meniscus begins to diminish



- Increasing the temperature further causes the gas and liquid densities to become more similar. The meniscus is less easily observed but still evident



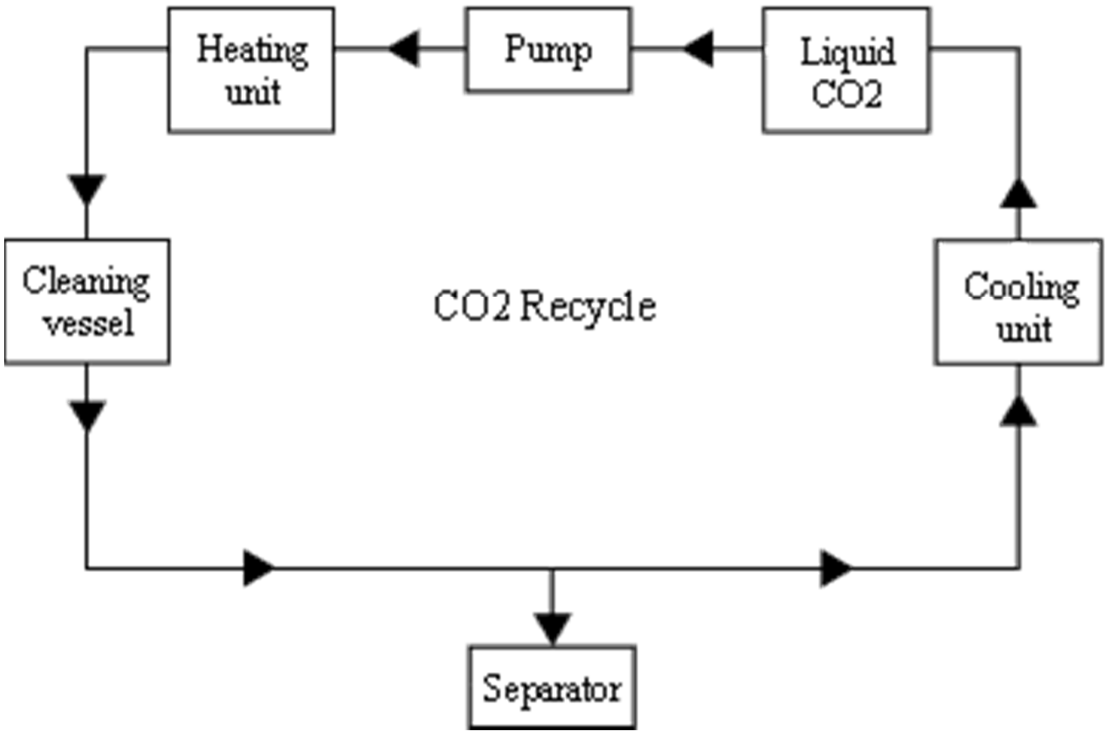
- Once the critical temperature and pressure have been reached the two distinct phases of liquid and gas are no longer visible. The meniscus can no longer be seen. One homogenous phase called the "supercritical fluid" phase occurs which shows properties of both liquids and gases



SUPERCRITICAL CARBON-DIOXIDE CLEANING

- Cleaning with CO_2 is advantageous from an environmental standpoint
  - CO_2 is non-flammable, virtually inert, and is not an ozone-depleting compound.
  - After cleaning, the only wastes stream generated are the contaminants that were removed from the part that was cleaned.
  - There are no large, liquid streams to treat (as there is with aqueous cleaning)
  - No air streams to treat (as is the case with some solvent cleaning solutions).

Figure 2. Basic schematic of a supercritical carbon-dioxide cleaning system.



$SCCO_2$ cleaning system

- CO_2, which may be stored as a gas or in liquid form, is compressed above its critical pressure by a pump.
- The compressed CO_2 is then heated above its critical temperature in a heater, or sometimes in the cleaning chamber, making it $SCCO_2$.
- Any parts in the cleaning chamber are cleaned by exposure to the $SCCO_2$.
- Typically the cleaning chamber will include an impeller to promote mixing.

- $SCCO_2$-containing dissolved contaminants are then bled off to a separator vessel, where the $SCCO_2$ is decompressed and returned to a gaseous state.

- The contaminants remain in liquid form and are collected out the bottom of the separator, while the gaseous CO_2 is sent through a chiller to return it to a liquid form for storage to be reused again.

- This closed-loop recycling of the CO_2 means that only a small portion of the cleaning solution has to be replaced over time due to system leakage.

- The now clean parts can be removed from the chamber and are immediately ready for the next step in the manufacturing process, since no drying or rinsing is required to remove residual cleaning solution.

- There are also a number of practical advantages associated with the use of supercritical carbon dioxide as a solvent.
- Product isolation to total dryness is achieved by simple evaporation.
- This could prove to be particularly useful in the final steps of pharmaceutical syntheses where even trace amounts of solvent residues are considered problematic.

- There are also two very useful complementary routes to particle formation with SCFs and supercritical carbon dioxide in particular,

  - rapid expansion of supercritical solutions (RESS) search: supercritical fluid RESS site:www.pnl.gov and

  - supercritical anti-solvent precipitation (SASP) (http://www.nottingham.ac.uk/supercritical/scantsol.html).

- One of the main differences between supercritical fluids and conventional solvents is their compressibility.
  - Conventional solvents in the liquid phase require very large pressures to change the density,
  - For supercritical fluids, very significant changes in density and hence solvating properties can be achieved by comparatively small pressure and/or temperature changes, particularly around the critical point.

- Supercritical fluids are considerably <u>less dense than conventional solvents.</u>
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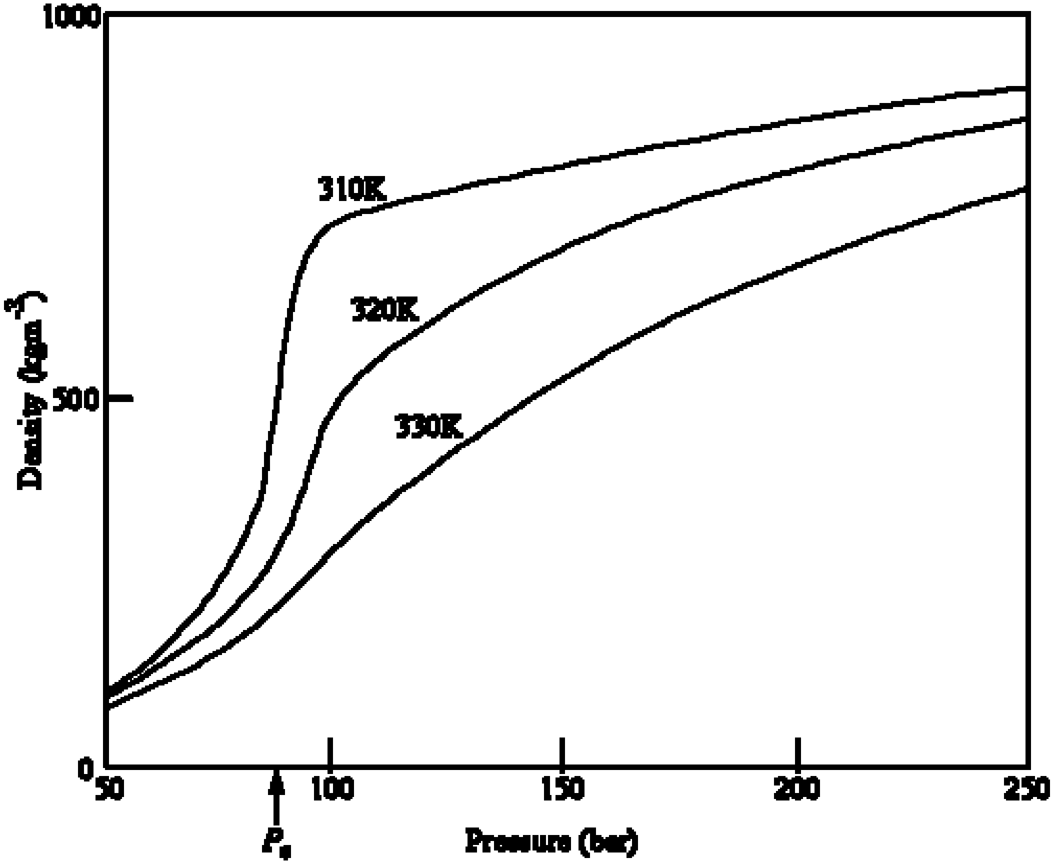
- This can lead to problems of solubility in some cases, but also means they are considerably <u>less viscous than conventional solvents which lead to a significantly greater diffusivity.</u>
- This can result in significantly faster reaction rates if diffusion is rate limiting.


1000
500
0
Density (kgm^{-3})
310K
320K
330K
50
100
150
200
250
P_c
Pressure (bar)

Water as a Reaction Solvent

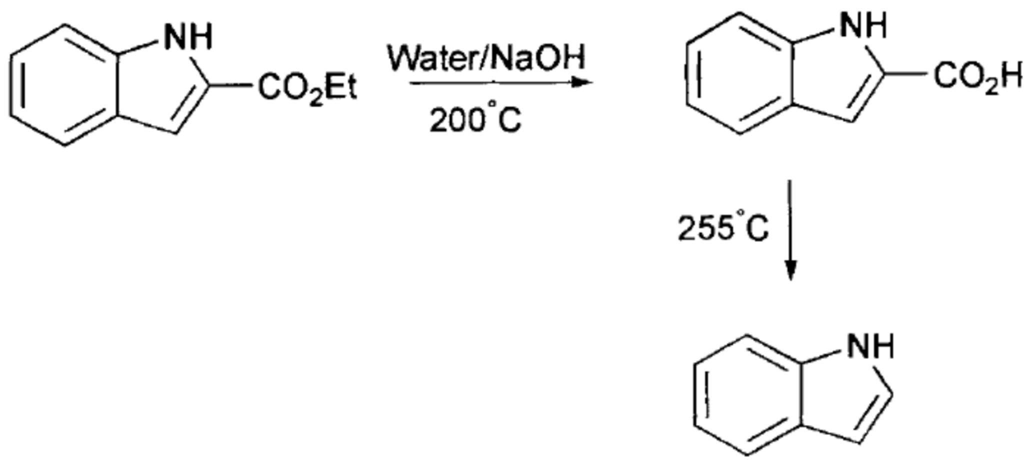
- Water is not a good solvent for carrying out synthetic organic reactions, because of either its poor solvent properties or the hydrolytic instability of reagents or products.

- The temperature of water is raised the ionic product increases whilst its density and polarity decrease.

- Thus at temperature above 200^{o}C (in the liquid state) water starts to take on many of the properties of organic solvents.

- At 300^{o}C water has solvent properties similar to acetone. These effects are related to the reduction in hydrogen bonding by water at higher temperatures.

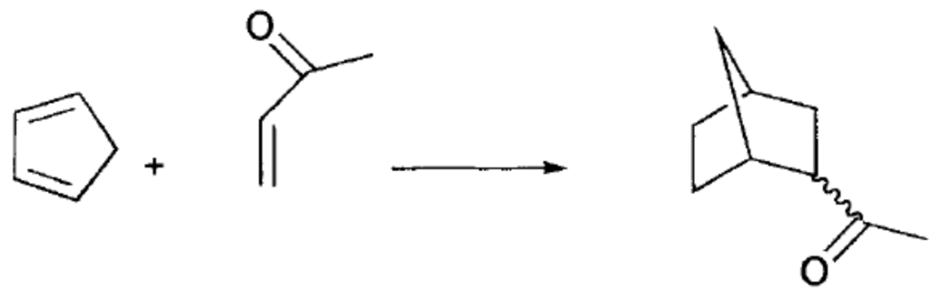
- Reaction such as hydrolysis of indole carboxylic acid esters gives synthetic versatility.
- At 200ºC the esters are rapidly hydrolysed in high yield in the presence of small amount of base,
- but at 255ºC the resulting carboxylic acid is decarboxylated in over 90% yield within 20 min.
- This decarboxylation step also has the environmental advantages when compared to more usual methods involving use of copper catalysts in non-volatile organic bases at high temperatures.


NH
CO2Et
Water/NaOH
200°C
NH
CO2H
255°C
NH

The use of water as a solvent for Diels-Alder reactions

- The reaction between cyclopentadiene and butanone was over 700 times faster in water than in many organic solvents.
- This increased rate has been attributed to the hydrophobic effect. <u>Owing to the difference in polarity between water and the reactants</u>,
- <u>Water molecules tend to associate amongst themselves, excluding the organic reagents and forcing them to associate together forming small drops, surrounding water</u>.

- A further method of increasing the rate of Diels-Alder reactions in water is the salting-out effect.
- Salt such as lithium chloride is added to the aqueous solution. In this case water molecules are attracted to the polar ions increasing the internal pressure and reducing the volume.
- This has the effect of further excluding the organic reagents.



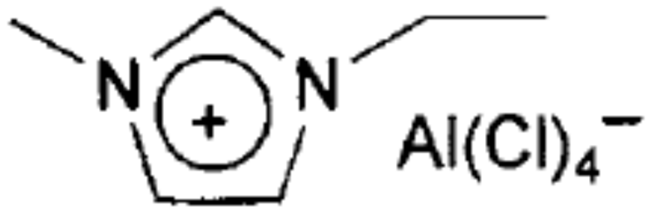
Solvent	Approx. relative rate
isooctane	1
methanol	12.5
water	740
water/LiCl	1800

Ionic liquids

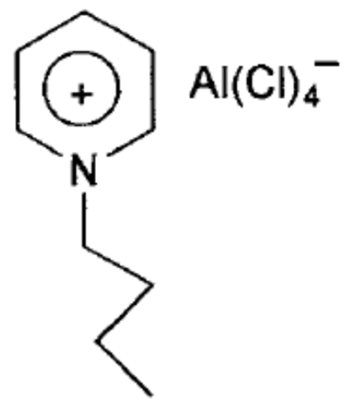
- The major advantage of using ionic liquids as solvents is their very low vapour pressure, which coupled with the fact that they can often act as catalyst and solvent

- they are liquid at low temperatures, this being due to poor packing of the respective ions, which are made from relatively large, non-coordinating, asymmetric ions.

- 1-ethyl-3-methylimidazolium chloride-aluminium(III) chloride



- N-butylpyridinium-aluminium(III) chloride



Properties common to most ionic liquids that make them attractive reaction solvents

- Tunability – by varying the cation/anion ratio, type and alkyl chain length properties such as acidity/basicity, melting temperature and viscosity can be varied to meet particular demands
- Many ionic liquids are stable at temperatures over 300°C, providing the opportunity to carry out high-temperature reactions at low pressure.
- Ionic liquids that are not miscible with organic solvents or water may be used to aid product separation or used in liquid-liquid extraction processes.

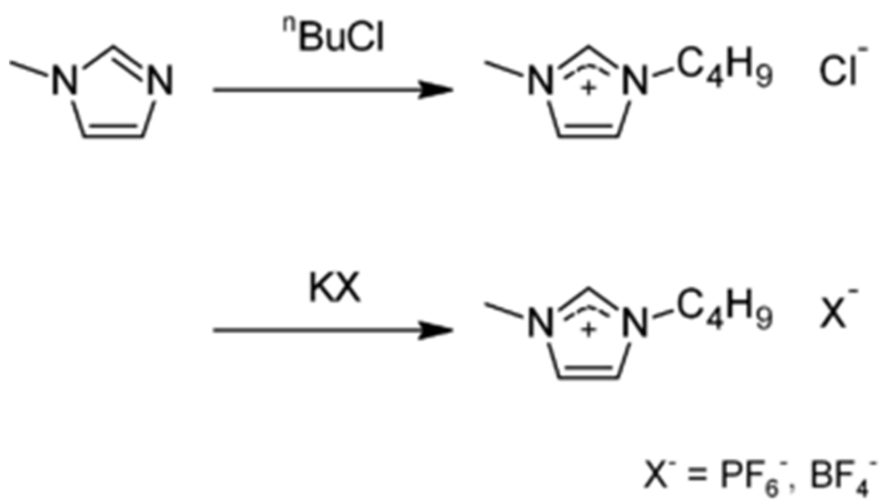
Ionic Liquids as Catalysts

- The highly acidic properties of [emim]$AlCl_4$ have been used in several cationic alkene oligomerization reactions

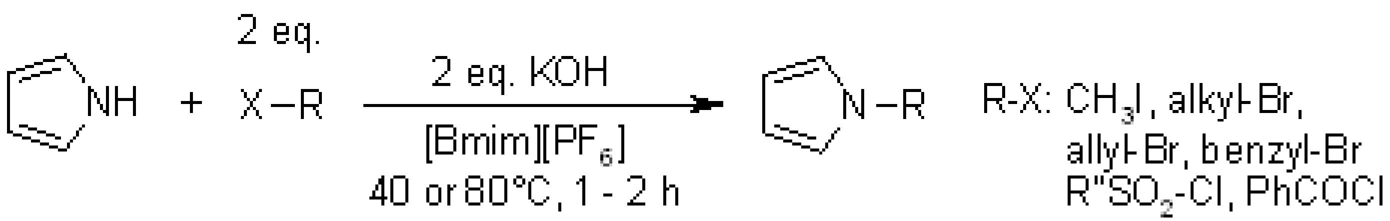
- Such reactions are rapids, with conversion well over 90% being achieved within 30 min.

Ionic Liquids as Solvents

- 1-Butyl-3-methylimidazolium hexafluorophosphate, also known as BMIM-PF6,
  - a viscous, colourless, hydrophobic and non-water soluble ionic liquid.
- BMIM-Cl is synthesized by alkylating 1-methylimidazole with 1-chlorobutane



- a highly regioselective N-substitution of pyrrole with alkyl halides, sulfonyl chlorides, and benzoyl chloride gave substituted pyrroles in excellent yields.



Fluorous Biphase Solvents

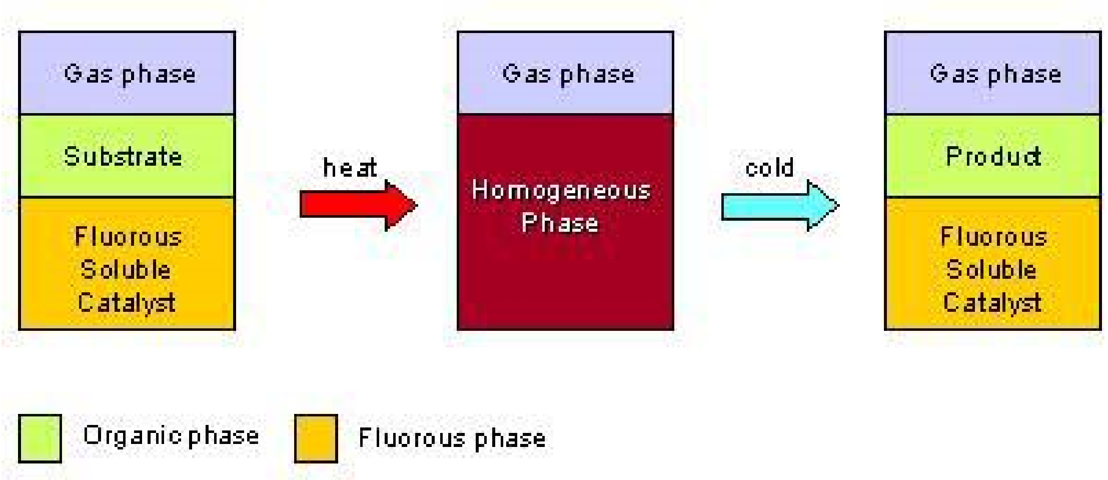
- The physical properties of fluorinated fluids offer a means of total separation between product and catalyst
- This occurs by retention of the catalyst in the fluorinated phase by derivisation with highly fluorinated backbones.
- Fluorous biphase catalysis offers a solution to this problem, with total post reaction product/catalyst separation, implying maximum yield and minimum waste.

Components of FBS

- a fluorous phase, normally a perfluorocarbon solvent containing a dissolved catalyst and
- a second organic or aqueous phase, containing a dissolved substrate, which has limited solubility in the fluorous phase

- The advantage of the FBS is that certain mixtures of organic and PFC solvents become completely miscible at elevated temperatures allowing reactions to proceed homogeneously.

- On cooling the phases separate allowing the catalyst/product separation.



- the use of fluorous biphase systems may be expected to work best when the reactants are non-polar but the polarity of the products is relatively high.

- Cobalt-fluorinated porphyrin complexes have been successfully used for the selective epoxidation of several cycloalkenes using oxygen in the presence of 2-methylpropanal.